

Medium Access Control and Routing Protocols for Wireless Mesh Networks

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4.1 Introduction

Wireless mesh networks (WMNs), a.k.a. *community wireless networks*, have emerged to be a new cost-effective and performance-adaptive network paradigm for the next-generation wireless Internet. Targeting primarily for solving the well-known *last mile problem* for broadband access [1, 2], WMNs aim to offer *high-speed coverage at a significantly lower deployment and maintenance cost*. As shown in Fig. 4.1, most of the nodes are stationary in WMNs. Only a fraction of nodes have direct access, and will serve as gateways, to the Internet. In addition, several nodes serve as relays forwarding traffic from other nodes (as well as their own traffic) and maintain network-wide Internet connectivity, while the remaining nodes send frames along dynamically selected ad-hoc paths to the gateway nodes with Internet access. WMNs are preferable to existing cable/DSL based networks or wireless LANs (that provide WiFi access), due to the following advantages: (i) mesh networks are more cost-effective as service providers do not have to install a wired connection to each subscriber (\$20–\$50K per square mile to establish access, approximately 1/4 of the cost incurred in high speed cable access); (ii) mesh networks are inherently more reliable since each node has redundant paths to reach the Internet; (iii) the throughput attained by a mesh network user can be, in principle, increased through routing via multiple, bandwidth-abundant paths (in contrast, in WLANs the shared bandwidth decreases as the number of users within a HotSpot increases); and (iv) WMNs can readily extend their coverage by installing additional ad-hoc hops.

Several cities are planning or have partially deployed WMNs, such as *Bay Area Wireless Users Group (BAWUG)* [3], *Champaign-Urbana Community Wireless Network (CUWiN)* [4], *SFLan* [5], *Seattle Wireless* [6], *Southampton Open Wireless Network (SOWN)* [7], and *Wireless Leiden* (in Netherlands) [8]. The academic/research efforts are, on the other hand, represented by the MIT *Roofnet* project [9], the Rice University *Technology for All* project [10], and the MSR *Self-organizing neighborhood wireless mesh networks* project [1]. Although initial successes have been reported in these efforts, a number of performance related problems have also been identified. Excessive packet losses [11–13], unpredictable channel behaviors [11, 12],

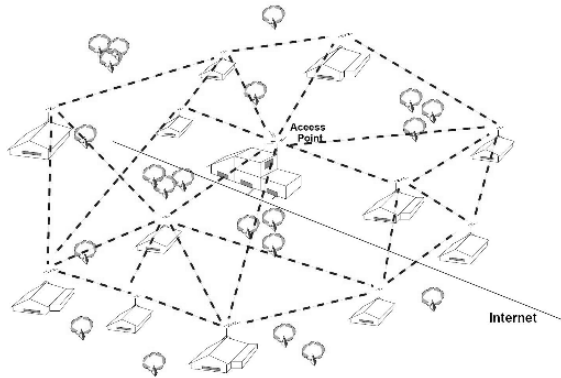


Fig. 4.1. Wireless mesh network.

inability to find stable and high-throughput paths [11, 12], and throughput degradation due to intra-flow and inter-flow interference [13–15] are among those most cited.

All these problems are rooted in the fact that *the notion of a link is no longer well-defined in wireless environments*. In network theory and practice, a link is usually characterized by its bandwidth, latency, packet loss ratio and patterns. However, in a WMN, a wireless medium is *shared* among nodes, and the *sharing range* is determined by (i) several PHY/MAC attributes such as the transmit power, the carrier sense threshold, and the channel on which an interface sends/receives frames, (ii) intra- and inter-flow interference (which in turn is contingent upon how nodes and traffic are distributed in the spatial and temporal domains), and (iii) environmental factors, such as multi-path fading and shadowing effects, temperature and humidity variation, and existence of objects in between. As a result, all the definitive metrics that characterize a link are no longer *well-defined* for a wireless link. All the protocols that were devised, and well-suited, for wireline networks will likely yield poor performance or even fail in WMNs. For example, as shown in [11] and [16], the shortest path algorithm with the hop count as the link metric will likely identify paths that are composed of long, lossy links with low bandwidth.

To solve (or at least mitigate) the above problems, one should (a) characterize how, and to what extent, wireless links are affected by PHY/MAC attributes and other environmental factors, (b) identify control knobs in the PHY/MAC layers with which the sharing range of a wireless link can be better controlled, and (c) understand the implication of making available these PHY/MAC attributes to higher-layer protocols on system performance optimization. Central to issues (a) and (b) is medium access control (MAC), while issue (c) is usually termed as cross layer design and optimization.

In this chapter, we discuss the state of the art in designing and implementing MAC for WMNs in Section 4.2. In particular, we categorize existing MAC-related re-

search into four categories: (1) controlling the sharing range of the wireless medium and increasing spatial reuse; (2) exploiting temporal/spatial diversity; (3) exploiting availability of multiple channels; and (4) exercising rate control. We also introduce in Section 4.3 a modular programming environment, termed as the *Transport Device Driver (TDD)*, that exports the PHY/MAC attributes via well-defined APIs and facilitates cross layer design and optimization, as a case study of cross layer design and optimization. We then present various routing protocols that take advantage of PHY/MAC attributes (such as channels) for route optimization in Section 4.4. We discuss open research issues in Section 4.5. Finally, our conclusion follows.

4.2 Medium Access Control in WMNs

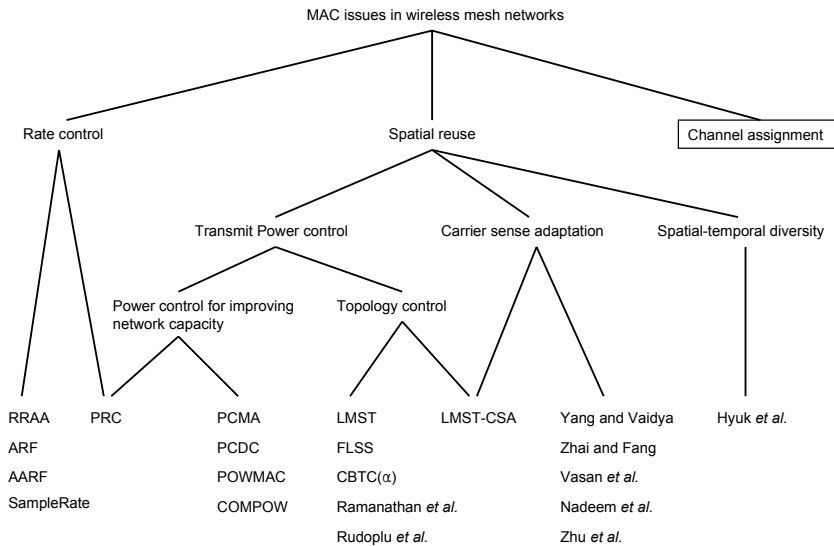


Fig. 4.2. A taxonomy of MAC issues in WMNs.

The major function of MAC in WMNs is to arbitrate access to the open and shared medium, with the objective of maximizing network capacity and achieving some level of fairness among users. In particular, there are several PHY/MAC attributes that can be used to improve spatial reuse, mitigate interference and maximize network capacity: (i) the *transmit power* each node uses for communications, (ii) the *carrier sense threshold* each node uses to determine if the shared medium is idle,

(iii) the *channel* on which the node transmits, and (iv) the *time intervals* in which each node gains access to the channel. Note that the carrier sense threshold specifies the received signal strength above which a node determines that the medium is busy and will not attempt for transmission. The first two attributes control the sharing range of the wireless medium in the spatial domain and ultimately the degree of spatial reuse. The third attribute exploits use of non-overlapping channels to mitigate interference. The last attribute leverages temporal/spatial diversity and aims to schedule transmission of packets that may potentially interfere with one another in different time intervals. All these attributes affect the signal-to-interference-plus-noise ratio (SINR) at a receiver. Because the SINR is directly related to the data rate which a transmission can sustain, another PHY/MAC attribute that can be tuned to enhance the overall system performance is the data rate. Fig. 4.2 gives a taxonomy of MAC research issues in WMNs. Note that the issue of channel assignment (which is boxed in Fig. 4.2) is related to the topics to be discussed in Section 4.4, and is further categorized in Fig. 4.5. In what follows, we first outline research issues for each PHY/MAC attribute, and then summarize the state of the art.

(1) Controlling the Sharing Range of the Wireless Medium and Increasing Spatial Reuse

One can increase the level of spatial reuse by either reducing the transmit power or increasing the carrier sense threshold (thereby reducing the carrier sense range). The first research issue is how each node determines its transmit power and carrier sense threshold (in a distributed and self-adjusting manner) so that (i) network connectivity is maintained; (ii) the MAC-level interference is mitigated; and (iii) the spatial reuse is utilized (i.e., as many concurrent connections as possible are enabled, subject to maintaining necessary SINR for decoding at certain data rates).

Several interesting related research issues are – What is the relationship between the transmit power and the carrier sense threshold? Will tuning one parameter implies the other? What is the trade-off between (i) increasing the level of spatial reuse by using smaller power or larger carrier sense threshold and (ii) decreasing individual data rates each node can afford (because of the decrease in the SINR as a result of using smaller power/larger carrier sense threshold)? Specifically, when the transmit power decreases, the SINR decreases as a result of the smaller received signal [17, 18]. Similarly, when the carrier sense threshold increases, a node may determine the medium to be idle when some other concurrent transmissions (whose signals received at the node do not exceed T_{cs}) are in progress. This leads to the increase in the interference level and the decrease in the SINR. In both cases, the receiver may not be able to correctly decode the signal and the data rate sustained by each transmission may decrease. Finally, what is the minimal information that needs to be exchanged among mesh nodes in order to realize a (sub-)optimal solution (if any)? Answers to these questions are important research issues in order to fully exploit spatial reuse.

(2) *Exploiting Temporal/Spatial Diversity*

Another dimension of improving the network capacity is through *joint temporal and spatial diversity*. Specifically, the overall capacity can be increased by exploiting spatial diversity that exists among a number of multi-hop paths. Packets that are routed along these paths can be scheduled to take place simultaneously if their transmissions do not interfere with each other (significantly). In this manner, even if only single channels are available (e.g., without multi-radios or multi-channels) it is possible that the achievable throughput on a multi-hop wireless path is *only* limited by intra-flow interference.

There are, however, two issues that must be addressed in order to realize spatial diversity. First, the set of paths along which transmissions can take place with the least inter-flow interference must be identified, perhaps with received signal strength measurements. Second, based on the set of non-interfering paths, the order in which packets of different connections are scheduled to be transmitted must be determined, with the objective of mitigating interference.

(3) *Exploiting Availability of Multiple Channels*

Traditional multi-hop wireless networks are mostly comprised of single-radio nodes. Such networks may suffer from capacity degradation due to the half-duplex transmission capability of the wireless medium. A solution is thus to equip nodes with multiple radio interfaces and assigning orthogonal channels to radios. In this manner, nodes can communicate simultaneously with the minimal interference, although they are within the interference range of each other. Even in networks with only single-radio nodes, capacity improvement can be expected by enabling nodes with the interference range of each other to operate on different channels to minimize the amount of interference. Currently the IEEE 802.11b/g and IEEE 802.11a standards provide, respectively, 3 and 12 orthogonal channels which can be used simultaneously within a neighborhood.

A simple design for multi-radio and multi-channel networks would be to equip each node with the same number of radios as the number of orthogonal channels. However, due to both the economical and technical reasons only a limited number of radios may be equipped at each node. The research issue is then how each node determines the channel on which each of its radios will operate, in order to reduce the interference caused by simultaneous transmissions on the same channel. Moreover, channel assignment is usually considered in conjunction with routing (Section 4.4). How to jointly select a route and assign channels to radio interfaces along the route is an important and active research area.

(4) *Exercising Rate Control*

Rate control refers to the process of dynamically adapting the data rate according to the channel status, with the aim of choosing an optimal data rate for the given channel condition. An example is the auto-rate function available in most IEEE 802.11 a/b/g chipsets. There are 4 data rates (1, 2, 5.5, 11 Mb/s) available in 802.11b and 8 data

rates (6, 9, 12, 18, 24, 36, 48, 54 Mb/s) available in 802.11 a/g. Usually the higher the SINR, the higher the data rate. For a given SINR, one may then choose the highest possible data rate (that allows correct decoding) in order to maximize the throughput.

The procedure of rate control consists of two phases: *channel estimation* and *rate selection*. The major research issues to be considered are: (i) which metric should be used to measure the channel quality? and (ii) which design rule associated with the metric should be used to select a new data rate?

4.2.1 Transmit Power Control

Graph-Model-Based Topology Control

The issue of transmit power control has been extensively studied in the context of topology maintenance by graph-theoretic approaches [19]- [27], where the major objective is to reduce power consumption, mitigate MAC interference, while preserving network connectivity. Since the energy required for transmission increases with the distance (at least in the order of two), it makes sense from the perspective of energy saving to replace one long link with several short links. Furthermore, reducing the transmit power also mitigates MAC interference, which in turn improves the network capacity (as a result of less MAC-level collisions and retransmissions). However, the transmit power cannot be reduced to the extent that network connectivity is not preserved.

A common notion of neighbors adopted in these power control algorithms is that two nodes are considered neighbors and a wireless link exists between them in the corresponding communication graph, if their distance is within the transmission range (as determined by the transmit power, the path loss model, and the receiver sensitivity). Algorithms that adopt this notion are collectively called *graph-model-based topology control*. Under this notion, topology control aims to keep the node degree in the communication graph low, subject to the network connectivity requirement. This is based on the common assertion that a low node degree usually implies low interference.

Rodoplu *et al.* [26] introduced the notion of *relay region* and *enclosure* for the purpose of power control. For any node i that intends to transmit to node j , node j is said to lie in the relay region of a third node r , if node i will consume less power when it chooses to relay through node r instead of transmitting directly to node j . The enclosure of node i is then defined as the union of the complement of relay regions of all the nodes that node i can reach by using its maximal transmission power. It is shown that the network is strongly connected if every node maintains links with the nodes in its enclosure and the resulting topology is a minimum power topology. A two-phase distributed protocol was then devised to find the minimum power topology for a static network. In the first phase, each node i executes local search to find the enclosure graph. This is done by examining neighbor nodes which a node can reach by using its maximal power and keeping only those that do not lie in the relay regions of previously found nodes. In the second phase, each node runs the distributed Bellman-Ford shortest path algorithm upon the enclosure graph, using the

power consumption as the link cost. When a node completes the second phase, it can either start data transmission or enter the sleep mode to conserve power. To deal with limited mobility, each node periodically executes the distributed protocol to find the enclosure graph. This algorithm assumes that there is only one data sink (destination) in the network, which may not hold in practice. Also, an explicit propagation channel model is needed to compute the relay region.

Ramanathan *et al.* [25] presented two centralized algorithms, i.e., CONNECT and BICONN-AUGMENT, to minimize the maximum power used per node while maintaining the (bi)connectivity of the network. CONNECT is a simple greedy algorithm that iteratively merges different components until only one remains. Augmenting a connected network to a bi-connected network is done by BICONN-AUGMENT, which uses the same idea as in CONNECT to iteratively build the bi-connected network. In addition, a post-processing phase can be applied to ensure per-node minimality by deleting redundant connections. Two distributed heuristics, LINT and LILT, are introduced for mobile networks. In LINT, each node is configured with three parameters - the desired node degree d_d , a high threshold d_h on the node degree, and a low threshold d_l . Every node will periodically check the number of active neighbors and change its power level accordingly, so that the node degree is kept within the thresholds. LILT further improves LINT by overriding the high threshold when the topology change indicated by the routing update results in undesirable connectivity. Both CONNECT and BICONN-AUGMENT are centralized algorithms that require global information, thus cannot be directly deployed in the case of mobility. On the other hand, the proposed heuristics LINT and LILT cannot guarantee that network connectivity is preserved.

CBTC(α) [19] is a two-phase algorithm in which each node finds the minimum power p such that transmitting with p ensures that it can reach some node in every cone of degree α . The algorithm was analytically shown to preserve network connectivity if $\alpha < 5/6$. It also ensured that every link between nodes is bi-directional. Several optimizations to the basic algorithm are also discussed, which include: (i) a shrink-back operation can be applied to allow a boundary node to broadcast with less power, if doing so does not reduce the cone coverage; (ii) if $\alpha < 2/3$, asymmetric edges can be removed while maintaining network connectivity; and (iii) if there exists an edge from u to v_1 and from u to v_2 , respectively, the longer edge can be removed while preserving connectivity, as long as $d(v_1, v_2) < \max(d(u, v_1), d(u, v_2))$. An event-driven strategy was proposed to reconfigure the network topology in the case of mobility. Each node is notified when any neighbor leaves/joins the neighborhood and/or the angle changes. The mechanism used to realize this requires state to be kept at, and message exchanges among neighboring nodes. The node then determines whether it needs to rerun the topology control algorithm.

Li and Hou [24] proposed a topology control algorithm, called *Local Minimum Spanning Tree (LMST)*, for multi-hop wireless networks with limited mobility. The topology is induced by having each node build its local MST independently (with the use of information locally collected) and only keep one-hop on-tree nodes as neighbors. Specifically, LMST is composed of three phases: *information collection*, *topol-*

ogy construction, and determination of transmit power, and an optional optimization phase: construction of topology with only bidirectional edges. In the information exchange phase, the information needed by each node for topology construction is obtained by having each node broadcast periodically a Hello message using its maximal transmit power. A Hello message should at least include the node id and the position of the node. In the topology construction phase, each node independently applies Prim's algorithm [28] to obtain its local minimum spanning tree. Then, by measuring the received signal strength of a Hello message, each node determines the specific power level necessary to reach each of its neighbors in the phase of determining transmit power.

LMST can further optimize the topology by replacing all the uni-directional links with bi-directional ones. To this end, every node may probe each of its neighbors to find out whether or not the corresponding edge is uni-directional, and in the case of a uni-directional edge, either deletes the edge or notifies its neighbor to add the reverse edge. The capability of forming a topology that consists of only bi-directional links is important for link level acknowledgments, and critical for packet transmissions and retransmissions over the unreliable wireless medium. It has been proved that LMST possesses several desirable properties: (i) the topology constructed under LMST preserves network connectivity; and (ii) the degree of any node in the resulting topology is bounded by 6. LMST has been also extended to include heterogeneous networks [21, 22], where the maximum transmit power can be different for each node, and to maintain k -connectivity ($k \geq 2$) [20, 23].

In spite of all the efforts in deriving all the graph theoretically grounded results, the underlying assertion that a low node degree usually implies low interference does not actually hold under the physical *Signal-to-Interference-Noise-Ratio* (SINR) model. As discussed in [29–31], this is because under the physical model, whether the interference — the sum of all the signals of concurrent, competing transmissions received at the receiver — affects the transmission activity of interest depends on the SINR at the receiver, which in turn depends on the transmit power of all the transmitters and their relative positions to the receiver of interest. The node degree under the graph model, however, does not adequately capture interference. In particular, a transmission of interest may fail because another concurrent transmission causes the SINR at the receiver to fall below the minimal SINR required for the receiver to decode the symbols correctly. This could occur even if the competing transmitter is outside the transmission range of the receiver. There are two undesirable consequences as a result of the inadequacy of graph-model-based topology control under the physical model. First, because the node degree does not capture interference adequately, the interference in the resulting topology may be high, rendering low network capacity. Second, a wireless link that exists in the communication graph may not in practice exist under the physical model, because of high interference (and consequently low SINR). As a result, the network connectivity may not even be sustained.

Power Control for Improving Network Capacity

Use of transmit power control for maximizing network capacity has been considered in [32]-ch04-Muqattash:04. Monks *et al.* [33] proposed the *Power Controlled Multiple Access (PCMA)* algorithm, in which the receiver advertises its interference margin that it can tolerate on an out-of-band channel and the transmitter selects its power in order not to disrupt any ongoing transmissions. Similar to IEEE 802.11 RTS/CTS handshake, PCMA uses RPTS/APTS handshake to decide the minimal transmission power for successful frame reception. PCMA further introduces an additional channel, i.e., the busy tone channel in order to implement the noise tolerance advertisement. Any transmitter must sense the busy tone to decide its transmit power for a minimum time period. As compared to the IEEE 802.11 protocol, PCMA can improve the throughput by more than a factor of two in high-density networks.

Muqattash and Krunz proposed a similar power control protocol, called *Power Controlled Dual Channel (PCDC)* [34]. The PCDC protocol constructs the network topology by overhearing RTS/CTS packets, and the computed interference margin is announced on an out-of-band channel. The basic idea of PCDC is to employ a distributed algorithm for computing a minimal connectivity set (i.e., a minimum set of nodes that guarantees connectivity of the node to the network) in order to find the lowest possible power level while preserving the network connectivity and proper MAC functions. As compared to the IEEE 802.11 standard, PCDC can achieve improvements of up to 240% in channel utilization and over 60% in end-to-end throughput, and a reduction of more than 50% in energy consumption. However, it should be noted that the adaptive computing process for the connectivity set may require extensive computing overhead at each node. Muqattash and Krunz also proposed a single channel protocol called *POWMAC* [35] for exchanging the interference margin information.

Narayanaswamy *et al.* [36] developed a power control protocol, called *COMPOW*. The authors argued that if each node uses the smallest common power required to maintain network connectivity, the traffic carrying capacity of the entire network is maximized, the battery life is extended, and the contention at the MAC layer is reduced. In COMPOW each node runs several routing daemons in parallel, one for each power level. Each routing daemon maintains its own routing table by exchanging control messages at the specified power level. By comparing the entries in different routing tables, each node can determine the smallest common power that ensures the maximal number of nodes are connected. Specifically, let $N(P_i)$ denote the number of entries in the routing table corresponding to the power level P_i . Then the adequate power level for data packets is simply set to the smallest power level P_i for which $N(P_i) = N(P_{\max})$. The major drawback of COMPOW is its significant message overhead, since each node runs multiple daemons, each of which has to exchange link state information with the counterparts at other nodes. COMPOW also tends to use higher power in the case of unevenly distributed nodes. Finally, since the common power is collaboratively determined by the all nodes inside the network, global reconfiguration is required in the case of node joining/leaving.

4.2.2 Adaptation of Carrier Sense Threshold

Recently a number of studies have focused on exploiting IEEE 802.11 physical carrier sense to increase the level of spatial reuse [37]- [40]. By physical carrier sense, it means that before attempting for transmission, a node senses the medium and defers its transmission if the channel is sensed busy, i.e., the strength of the received signal exceeds a certain threshold CS_{th} . Carrier sense reduces the likelihood of collision by preventing nodes in the vicinity of each other from transmitting simultaneously, while allowing nodes that are separated by a safe margin (termed as the carrier sense range) to engage in concurrent transmissions.

Given a predetermined transmission rate, Zhu *et al.* [39] derived a simple condition for the carrier sense threshold, in order to cover the entire interference range for several regular topologies. Zhu *et al.* also proposed in [40] a dynamic algorithm for adjusting the carrier sense threshold to exploit spatial reuse. The algorithm calculates, based on the estimate of the current local interference condition, a near-optimal value for the carrier sense threshold. In this manner, the SINR at each node can be kept above the desired threshold by local measurement and information exchange. However, the proposed feedback algorithm is essentially heuristic based. Thus, the challenge remains on how to design a theoretically grounded, self-adapting algorithm for tuning the carrier sense threshold, with the aim of improving the network capacity.

Vasan *et al.* [38] proposed an algorithm, entitled *echos*, for on-line tuning of the carrier sense threshold in order to allow more flows to co-exist in IEEE 802.11-based hotspot wireless networks. Nadeem *et al.* [37] proposed a location-enhanced DCF algorithm that exploits location information to exploit spatial reuse for given transmission rates.

Yang and Vaidya [41] are perhaps the first to address the impact of physical carrier sense on Shannon capacity of single-rate, multi-hop wireless hoc networks, while *taking into account the MAC layer overhead*. Under the assumption of a dense network, they derived an analytical model that characterizes the relationship between the Shannon capacity and the carrier sense range. Note that they only considered first-tier interference in the calculation of SINR. Based on the derived model, they made the following key observations: (i) the MAC overhead has a fundamental impact on the selection of the optimal carrier sense threshold. By selecting a larger value of the carrier sense threshold, both the bandwidth-independent MAC overhead and the bandwidth-dependent MAC overhead can be reduced, which in turn, improves the utilization of each individual wireless link; and (ii) the optimal value of the carrier sense threshold depends on the level of channel contention, packet size, and other factors affecting the bandwidth-dependent and bandwidth-independent overheads. With the use of an inappropriate carrier sense threshold, the aggregate network throughput may severely degrade.

Zeng and Hou [42] analyzed IEEE 802.11 DCF in single-rate, multi-hop wireless networks with consideration of the effects of physical carrier sense, SINR, and collision caused by accumulative interference. Specifically, they substantially extended Cali's analytic model [43] and rigorously modeled, with these effects considered,

channel activities governed by IEEE 802.11 DCF in multi-hop wireless networks. They showed that as in WLANs, the choice of the contention window size can greatly impact the system throughput in multi-hop wireless networks. However, the optimal value of the contention window size is much smaller. This is because in multi-hop wireless networks, (i) physical carrier sense has already, to some extent, restricted nodes from accessing the medium, and (ii) a node may be silenced not only by transmissions in its vicinity, but also by accumulative interference that exceeds the carrier sense threshold. While a larger attempt probability increases the collision probability, it also helps to reduce the idle periods before successful transmissions, and mitigate the above effects. Moreover, given the minimal SINR threshold, the optimal carrier sense range is smaller than the conventional value used (provided that the contention window size is tuned accordingly). This suggests that, as long as the contention window size is appropriately controlled, the systems throughput can be further improved by allowing more concurrent transmissions and increasing spatial reuse.

Zhai and Fang [44] investigated the impact of physical carrier sense in multi-rate, multi-hop wireless networks where nodes have different levels of transmit power. They also considered the impacts of SINR, node topology, hidden/exposed nodes, and bidirectional handshakes to determine the optimal carrier sense range for maximizing the throughput. Through analysis and simulation, they made the following observation: (i) the optimal carrier sense threshold for one-hop flows does not seem to work well for multi-hop flows. This implies that characteristics unique to multi-hop flows should be carefully considered to find the optimal carrier sense threshold; this observation is consistent with that in [42]; (ii) the optimal carrier sense threshold derived for different data rates is similar to each other. This suggests that a single value of the carrier sense threshold can be used for different data rates; and (iii) without use of an adequate carrier sense threshold, higher data rate does not necessarily give higher throughput.

4.2.3 Joint Control of Transmit Power and Carrier Sense Threshold

Fuemmeler *et al.* [45] studied the relation between the transmit power and the carrier sense threshold in determining the network capacity. They concluded that transmitters should keep the product of their transmit power and carrier sense threshold fixed at a constant, i.e., the lower the transmit power, the higher the carrier sense threshold (and hence the smaller the carrier sense range), and vice versa. A combination of lower transmit power and higher carrier sense leads to a large number of concurrent transmissions, with each transmission sustaining a small data rate. On the other hand, a combination of higher transmit power and lower carrier sense threshold leads to a small number of concurrent transmissions, with each transmission sustaining a large data rate. Although the analysis gives a general trend, it does not give guidelines on how to select the two parameters to *maximize* the network capacity.

Kim *et al.* [46] studied the relationship between physical carrier sense and Shannon capacity, and showed that (i) in the case that the achievable channel rate follows the Shannon capacity, spatial reuse depends only on the ratio of the transmit power to the carrier sense threshold; and (ii) in the case that only a set of discrete data rates

are available, tuning the transmit power offers several advantages that tuning the carrier sense threshold cannot, provided that there is a sufficient number of power levels available. Point (i) implies that, to improve (or in the best case optimize) network capacity, one can tune one parameter, while fixing the other at an appropriate value.

Yang *et al.* [47] extended both Bianchi's model [48] and Kumar's model [49], and characterized the channel activities governed by IEEE 802.11 DCF in single-rate, multi-hop wireless networks from the perspective of an individual sender. In particular, they incorporated the effect of PHY/MAC attributes, such as transmit power and physical carrier sense, that need not be considered in WLANs but become extraordinarily important in multi-hop wireless networks, and derive the throughput attained by each sender. With the use of the analytical model derived, they then investigated the impact of transmit power and carrier sense threshold on network capacity, and identified a simple operating condition under which the network may attain throughput that is close to its optimal value. Specifically, they found that high system throughput can be achieved when the area within the carrier sense range silenced by a sender s is reduced as much as possible *under the premise that it still covers the interference area of its intended receiver r* . This increases spatial reuse while not deteriorating collisions due to the hidden node problem.

Based on the insight shed from the above analytical model, Yang *et al.* [47] proposed a distributed and localized algorithm, called *Local Minimum Spanning Tree with Carrier Sense Adjustment (LMST-CSA)* that determines both the transmit power and the carrier sense threshold of a node. In LMST-CSA, each node determines its transmit power based on LMST [24], and then controls its carrier sense threshold so that the desirable operating condition is met. Simulation results show that *LMST-CSA* achieves higher throughput as compared to conventional IEEE 802.11 DCF, *LMST with no carrier sense adjustment*, and *LMST with static carrier sense adjustment*.

4.2.4 Exploitation of Spatial-Temporal Diversity

The problem of mitigating interference and improving network capacity was also considered from the angle of spatial-temporal diversity in [32]. Lim *et al.* focused on transporting downstream traffic at gateway nodes with Internet access and proposed to construct, based on the received signal strengths (RSS) measurements, a virtual coordinate system. This is in contrast to most existing work which relies on geographic locations of wireless mesh nodes. The reason for using RSS measurements, rather than geographic distances, among neighbors as the references is because RSS measurements are more "representative" in determining the level of interferences between nodes. Specifically, the RSS measurements between a node n and its neighbors are represented by the $p \times p$ square matrix $\mathbf{S}$, the columns of which can be considered as the coordinates of the corresponding nodes in a p -dimension space. Note that the i th column vector of $\mathbf{S}$ is the RSSs measured by the i th node from all the nodes. As these coordinates are correlated with each other, it is difficult to identify components that play an important role in determining the interferences. Hence Lim *et al.* constructed an orthogonal virtual coordinate system with a smaller dimensionality by using singular value decomposition, and used the "virtual distance" between mesh

nodes to infer the level of interferences between them. With the use of the coordinate system, they were able to determine the sets of paths along which transmissions can take place with the least inter-flow interference.

Based on the sets of non-interfering paths, a gateway node then determines the order in which a gateway node schedules frames of different connections to be transmitted. To allow a gateway node to send frames consecutively in a non-interruptible manner, we leverage the *transmission opportunity (TXOP)* option in the IEEE 802.11e specification [50]. That is, a gateway node that succeeds in grasping the medium is granted the right to use the medium for a period of time specified by TXOP. The gateway uses a TXOP to transmit multiple frames, with SIFS (instead of DIFS) as the inter-frame space *between* the sequence of DATA-ACK exchanges. If the DATA-ACK exchange has been completed, and there is still time remaining in the TXOP, the node may transmit another frame (after an idle time of SIFS), provided that the frame to be transmitted and its necessary acknowledgment can fit into the time remaining in the TXOP. The experimental results showed that the downstream throughput of a gateway node in a wireless mesh network can be improved by 10 - 35% under various network topologies and traffic distributions. Also, the proposed approach requires only minimal code change in the gateway nodes and does not require any extra hardware.

4.2.5 Exploitation of Channel Diversity Through Channel Assignment

Multi-channel MAC (MMAC)

The MMAC protocol [51] is motivated by the fact that most of the existing MAC protocols are designed for single-channel operations, although the IEEE 802.11 standard supports the use of multiple channels. Under MMAC, each node is equipped with only one transceiver, but can switch channels dynamically with the objective of mitigating interference and improving network capacity. To support dynamic negotiation of channels, the time is divided into fixed-time intervals using beacons, and a small window called the *ATIM window* at the beginning of each interval is used to negotiate channels for transmitting packets. In an ATIM window, all nodes listen to a pre-defined, default channel on which beacons and ATIM packets are transmitted. One important information in an ATIM packet is the *preferable channel list (PCL)* that indicates which channel is preferred for the node. PCL is maintained at both the source and the destination.

When a node receives an ATIM packet, it selects a channel and sends to the sender an ATIM-ACK packet that includes the selected channel. The channel to be selected is determined from (i) the information included in the PCL sent by the sender and (ii) the PCL locally kept. Also, the number of source-destination pairs that have selected a channel is counted by overhearing ATIM-ACK and ATIM-RES packets. The selection procedure that a node uses then attempts to balance the channel load as much as possible so that the bandwidth waste caused by contention and backoff is reduced. As the simulation study indicated, MMAC improves network throughput significantly, especially when the network is highly congested. This is, in part, due

to the fact that MMAC successfully exploits multiple channels to achieve higher throughput than IEEE 802.11 DCF.

Asynchronous Multichannel Coordination Protocol (AMCP)

AMCP is a distributed medium access protocol that utilizes multiple channels to address *starvation* in a multi-hop wireless network [52]. It is argued that a single-channel CSMA system may suffer from starvation when CSMA based access is used in a multi-hop environment. If the senders of two contending flows are not within the carrier sensing range of each other and have an asymmetric view of the channel state, then one transmitter may achieve significantly higher throughput than the other. This is because this transmitter does not experience collision, but the other suffers from RTS failures and exponential back-off. The starvation problem that thus arises is called *Information Asymmetry (IA)* problem. The other source of starvation is caused by the so-called *Flow-in-the-Middle (FIM)* problem. This problem occurs when the transmitter of a flow has neighboring transmitters which are not within the carrier sense range of each other. In this case, the middle flow can barely have any transmission opportunity since its transmission activities is deferred by neighboring nodes. Both IA and FIM problems are caused by the asymmetry of multi-hop topology and the use of carrier sense.

To cope with starvation, one simple approach is to keep separate channels for control and data transmission. This alleviates starvation since contentions only occur on the control channel for transmission of control packets whose length is comparable to the back-off period. Following this approach, AMCP designates a control channel for nodes to contend and reserve data channels by exchanging RTS/CTS packets according to 802.11 DCF. Once a control packet is exchanged successfully, both the sender and the receiver switch to the reserved data channel, and transmit a data packet. After a data packet is successfully transmitted on the reserved channel, the sender and receiver return to the control channel and set all channels as unavailable for a pre-determined time interval except the one just used. They may contend for the reserved data channel immediately or contend for other data channels after the specified time interval elapses. The simulation study showed that AMCP not only utilizes multiple channels to achieve a significant aggregate throughput gain (as compared to single-channel systems), but also adequately addresses the starvation problem.

MAXchop

Mishra *et al.* [53] addressed the fairness issue in IEEE 802.11 hotspot networks from the perspective of channel assignment. In an uncoordinated environment of hotspot access points, proper channel assignment is critical. The APs that implement channel assignment algorithms have to ensure that the total wireless bandwidth is divided fairly among interfering hotspot APs. No hotspot should have a higher priority on the total bandwidth over others, irrespective of the number of clients. Providing proportional fairness in this environment will require additional coordination between APs/clients across different management domains.

The MAXchop algorithm was proposed to utilize channel hopping to improve fairness of any existing channel assignment. In MAXchop, in each slot the APs utilize a specific channel assignment that may have been computed using existing distributed algorithms. In different slots, the APs utilize different channel assignments. The channel assignment used in a slot is different from that in the previous slot, but is yet locally the best. MAXchop enables the APs to utilize all the channel assignments so as to uniformly divide the available bandwidth among the APs. Consequently, this approach ensures that the long term throughput that each AP attains is averaged over multiple different channel assignments. Experiments results showed that with partially overlapped channels as well as with non-overlapped channels, MAXchop improves both fairness and throughput.

Component Level Channel Assignment (CLCA)

Practical considerations such as the switching delay and the synchronization and scheduling overheads greatly impact the performance of channel assignment. Vedantham *et al.* [54] utilized the concept of connected component as granularity of assignment to mitigate such overheads. This is in contrast to existing channel assignment algorithms which assign channels to packets, links, or flows. A connected component in a flow graph is the largest subgraph, such that there exists a path between any node to all the other nodes in the subgraph. Besides its simplicity, this algorithm has the following advantages: (i) there is no need to change the off-the-shelf radio hardware or MAC algorithms, and (ii) there is no synchronization requirement, channel scheduling overheads, or switching between channels to serve data flows.

Conceptually, this algorithm involves assigning a single channel to all the nodes which are included in a component (formed by nodes which make mutually intersecting flows). All links in a connected component induced by the underlying flow graph operate in a single channel. However, different connected components can potentially operate on different channels. The algorithm has two phases: *path selection* and *channel assignment*. In the path selection phase, paths that minimize the number of intersections in the network are selected and, components are built up with the selected paths. Once the component set has been determined, channels are assigned to the components obtained in the first phase. In the channel assignment phase, channels are so assigned that the contention between different components in the underlying flow graph is minimized.

Slotted Seeded Channel Hopping (SSCH)

Bahl *et al.* [55] proposed the *Slotted Seed Channel Hopping (SSCH)* protocol in which nodes with a single interface are allowed to switch across channels in such a way that nodes desiring to communicate overlap, while disjoint communications mostly do not overlap (and hence do not interfere) with each other. In SSCH, the time allocated to a single channel is defined as a slot, which is 10 ms in the implementation and corresponds to 35 packet transmission times at 54 Mbps. In SSCH, each device picks multiple (e.g., 4) sequences, each of which is uniquely determined by the seed of a pseudo-random generator, and follows them in a time-multiplexed

manner. When device A would like to talk to device B , it waits until it is on the same channel as B . If device A would like to talk to device B frequently, it adopts one or more of device B 's sequences, thereby increasing the time they are on the same channel.

For the channel hopping mechanism to work, the sender learns the current sequences the receiver uses, via a seed broadcast mechanism. Every node broadcasts its channel schedule in each slot so that nodes can know each other's channel hopping schedule. This is termed as *optimistic synchronization*. Schedules are updated in two ways: each node will loosely synchronize the slot's start and finish time with other nodes, or it will overlap another node's schedule if it is going to send packets to this node. Also, the node will delay channel switching when it is communicating with another node until it finishes. Another strategy called *partial synchronization* is used for assigning channels, changing schedule and preventing channel congestion from taking place. Simulation results showed that both in the single-hop and multi-hop cases, SSCH performs significantly better than IEEE 802.11a achieving significant capacity improvement.

4.2.6 Rate Control

Rate control algorithms have been studied quite extensively in [56]- [65], and some of them have also been implemented in real products [56, 60]. As mentioned above, rate control aims to adjust the channel data rate with respect to the time-varying channel status. In principle, rate control consists of two phases: *channel estimation* and *rate selection*. The most commonly used metrics for estimating the quality of a channel include probe packets [56, 60, 62], consecutive successes/losses [57, 60, 62], and SINR [57, 59, 65]. The commonly used design rules for selecting a new data rate are increasing/decreasing the data rate on consecutive transmission successes (packet losses) and exploiting probe packets to assess new rates.

Wong *et al.* [66] conducted a study on challenges of rate control and explored a new design space. They evaluated several critical design guidelines that have been followed by most of existing algorithms: (i) decreasing the data rate on severe packet loss, (ii) using probe packets to assess the new rate, (iii) using consecutive success/failure as the index to increase/decrease the data rate, (iv) using PHY metrics such as SINR to infer the new data rate. Their experiments surprisingly showed that the above guidelines can be quite misleading, and may result in severe throughput degradation of up to 70%. They then proposed a *Robust Rate Adaptation Algorithm (RRAA)* based on the following ideas. First, they used the short-term loss ratio to opportunistically guide the rate selection. Second, they leveraged the per-frame RTS option, and used an adaptive RTS filter to prevent collision losses. They showed that the throughput of RRAA can be improved up to 143% in realistic field trials, as compared to the well known algorithms such as ARF, AARF, and SampleRate.

Kim *et al.* [46] proposed a joint power and rate control algorithm from the perspective of maximizing the level of spatial reuse. Following their observation that spatial reuse depends only on the ratio of the transmit power to the carrier sense threshold (Section 4.2.3), they proposed to tune the transmit power, while keeping

the carrier sense threshold fixed at an appropriate value. Then, they devised a localized power and rate control algorithm, called *Power and Rate Control (PRC)*, which enables each transmitter to adaptively perceive and determine its transmit power and data rate. The transmit power is so determined that the transmitter can sustain the highest possible data rate, while keeping the adverse interference effect on the other neighboring concurrent transmissions minimal. Simulation studies showed that, as compared to existing tuning algorithms for the carrier sense threshold, PRC improves the network capacity for up to 22%.

4.3 Example Device Driver Support for Cross Layer Design and Optimization

As discussed in Section 4.1, the traditional notion of a link is no longer well-defined in wireless environments, because characteristics of wireless links are now determined by several PHY/MAC control knobs, as well as inter-flow interference, multipath fading, temperature and humidity variations, and/or the presence of obstacles in the communication path. This implies that in order to optimize the network performance, PHY/MAC attributes should be exported to higher layer protocols in order to enable cross layer design and optimization.

In addition to the above technical concerns, the lack of an open, modular programming environment also imposes a hindrance to the wide deployment of cross-layer design/optimization algorithms in WMNs. Although many of the previous efforts have made their source code available [3, 4, 6, 8, 9], the software (such as customized device drivers, address resolution modules, routing daemons, and name servers) is often implemented in an ad-hoc manner, lacks in structural modularity, and does not come with well-defined APIs for experimentation and performance tuning. This presents a major hurdle for networking researchers to neatly incorporate their research results in the most performance-efficient manner, and empirically assess the algorithm/protocol performance.

As an example programming environment, we introduce in this section the *Transparent Device Driver layer (TDD)* proposed by Kung *et al.* in [67] and situated above the IEEE 802.11 device firmware. As part of the CUWiN software, TDD leverages the Atheros chipset, and the open-source Madwifi driver [68] in Linux and similar device drivers in NetBSD.¹ Although commodity 802.11 interfaces typically partition the MAC functionalities between hardware/firmware on the card and the software driver running in the kernel, the Atheros chipset does not require the loading of firmware. The chipset instead relies on a *Hardware Access Layer (HAL)* module provided in the binary form only. The HAL module operates between the hardware and the device driver to manage many of the chip-specific operations and to enforce required FCC regulations. It is similar to firmware, in that it prevents users from setting invalid operating parameters, but implements fewer 802.11 functionalities than

¹Note that the Madwifi driver for Linux was originally derived from NetBSD.

other firmware. More desirably, it provides an interface for changing various device parameters, including the minimum and maximum contention windows.

4.3.1 Architecture and Major Components

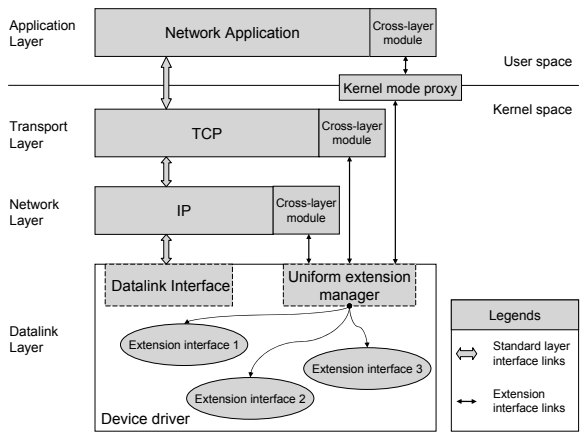


Fig. 4.3. The architecture of the uniform extension framework.

Fig. 4.3 shows the architecture of the transparent device driver (TDD). Different from the traditional layered approach, an extension-enabled device driver exports PHY/MAC parameters and events to higher-layer protocol modules. There are three major components in the TDD:

- Extension-enabled device driver:** The device driver has been extended to export a set of PHY/MAC attributes and events in the form of *extension specification*. The specification serves as a service agreement between the device driver and a higher-layer protocol module that uses it. To implements an extension, a device driver implements the get/set handlers of the PHY/MAC parameters. It also define events, provide the event information to the uniform extension manager, and notify the manager upon occurrence of events.
- Cross-layer control module:** A cross-layer control module implements a cross-layer design/optimization algorithm. As a client to the uniform extension manager, it registers itself with the uniform extension manager in order to use the facilities provided by the extension-enabled device driver. Through a generic interface, a control module can read and write PHY/MAC parameters exported by the driver. Also, it can subscribe to events of interest defined in an extension specification and provide the corresponding callback functions.

Uniform extension manager: The uniform extension manager is the major component of the TDD. We will elaborate on its internals in Section 4.3.2. Conceptually, it is responsible for (i) loading and unloading extensions, (ii) providing an API for cross-layer control modules to register events of interest and callback functions; (iii) allowing control modules to set/get PHY/MAC parameters via handlers registered by extensions; (iv) maintaining event definition and subscription; and (v) dispatching events to subscribing control modules.

Kernel mode proxy: For user-space programs to gain access to the TDD in the kernel, we introduce a *kernel mode proxy* that serves as a “bridge” between the two entities. Each uniform extension function exported is assigned an unique system call number. The kernel mode proxy is responsible for translating a TDD-related system call and invoking the corresponding uniform extension function, and (ii) delivering events to the handler in the user space.

4.3.2 Internals of Uniform Extension Manager

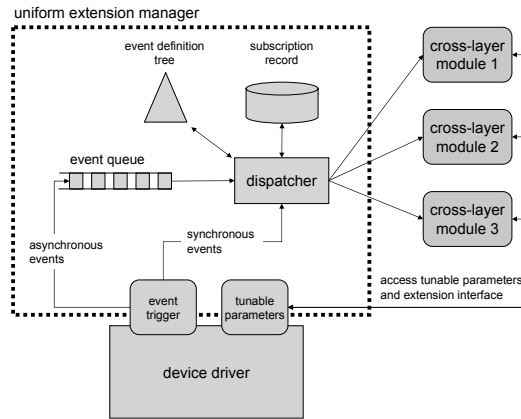


Fig. 4.4. Uniform extension manager and event delivery.

Fig. 4.4 shows the internals of the uniform extension manager and the data path in the event delivery mechanism. Table 4.3.2 lists the APIs exported by the uniform extension manager. The uniform extension manager maintains (i) the definition record of all the supported events in an event definition tree; and (ii) the list of subscribers of each event. A cross-layer control module (un-)subscribes to an event with a callback function by calling `AddEventHandler()` (`RemoveEventHandler()`). A device driver generates and delivers an event to the uniform extension manager (and subsequently cross-layer control modules that are interested in the event) by calling `TriggerEvent()`.

Table 4.1. The APIs defined in the uniform extension manager.

Category	Function name	Function description
Extension management	RegisterExtension()	Register/unregister an extension interface module.
	UnregisterExtInterface()	
	FindExtension()	
Register parameter set/get handlers	RegisterSetHandler()	Register or unregister a set handler to the uniform extension manager.
	UnregisterSetHandler()	
	RegisterGetHandler()	Register or unregister a get handler to the uniform extension manager.
	UnregisterGetHandler()	
Access to extension parameters	GetExtParam()	Get the value of an extension parameter by invoking the registered get handler.
	SetExtParam()	Set the value of an extension parameter by invoking the registered set handler.
Event Subscription and delivery	TriggerEvent()	Generate an event and deliver it to the subscribers.
	AddEventHandler()	Subscribe to an event with a callback handler function.
	RemoveEventHandler()	

Depending on the type of events, there are two possible paths for delivering an event to the manager. A *synchronous event* is an event for which the device driver requires feedback from its subscribers. When a synchronous event is triggered, it is delivered by the dispatcher immediately and the device driver that triggers the event waits until all the subscriber handlers are finished. An example of a synchronous event is a *transmit query*, in which prior to the transmission of a frame, the device driver may query the cross-layer control modules for recommendations on the transmit power, the channel on which the frame will be transmitted, or the data rate at which the frame will be transmitted. This facilitates realization of, for example, per-packet power control. Synchronous events make it possible for cross-layer control modules to make decisions upon occurrence of certain events. An *asynchronous event*, on the other hand, is a *notification* message sent by the device driver to the subscriber(s) of that event. Upon reception of an asynchronous event, the event trigger inserts the event into the event queue and wakes up the dispatcher. The dispatcher then delivers the event to the corresponding callback functions.

One point worthy of mentioning is how `TriggerEvent()` is implemented for asynchronous events. As many of the events are triggered by interrupts, `TriggerEvent()` is likely to be invoked by an interrupt handler. However, it is not safe to deliver events inside the context of interrupt handlers, since if for any reason the operation is delayed and the interrupt handler cannot finish, it may interfere the normal system operation. Therefore, we split the task into event creation and event delivery. The `TriggerEvent()` function only creates and puts the event into event queue. A separate kernel thread is created for the dispatcher. The dispatcher thread constantly monitors the event queue and is awakened only when there is a new event. In this manner, the overhead incurred in interrupt handlers is greatly reduced.

4.3.3 Desirable Features

The TDD has the following salient features:

Controlled transparency: The TDD provides a transparent and generic interface for higher-layer protocol modules to access, through well-defined APIs, a rich set of PHY/MAC attributes and functionalities in the device driver. Specifically, the following PHY/MAC attributes are available: (i) the transmit power level, (ii) the carrier sense threshold, (iii) the data rate, (iv) the receive signal strength index (RSSI), and (v) the channel used to transmit a frame/upon which a frame is received, and (v) the time instant at which a frame is scheduled for transmission/receive. (Note that to obtain the received signal strength, the driver has to instrument the HAL to query, upon receipt of a frame, the value of a specific hardware register). Through an event subscription mechanism, higher-layer protocol modules can also receive timely update of channel status, without directly inserting callback functions in various places of the device driver.

Flexibility: The design philosophy of the TDD (and at heart the uniform extension manager) is to provide minimum but crucial functionalities that enable implementation of complicated cross-layer design/control algorithms. The event subscription mechanism is simple, elegant, and allows *multiple* higher-layer protocol modules to subscribe, and be alerted of, PHY/MAC events of interest. They can also register with the event subscription mechanism their callback functions, allowing adequate actions to be taken upon event occurrence. Moreover, the TDD allows the time granularity at which PHY/MAC properties are controlled to be on a *per-packet* or *per-connection* basis, or *permanently* (i.e., until the property is reset).

Easy Integration and Portability: Existing upper-layer protocol modules (e.g., routing daemons) can be extended to subscribe events of interest (e.g., frame reception status upon frame arrival), and figure in the information in their decision making. Through dynamic module loading and extension registration, an upper-layer protocol can realize cross-layer optimization if an extension has been implemented, and it falls back to the normal operation if the required extension is not supported by the TDD. This ensures portability.

4.4 Routing That Leverages PHY/MAC Attributes in WMNs

As discussed in Section 4.3, with the availability of a modular programming environment that exports PHY/MAC attributes and events to higher-layer protocols, numerous cross-layer design and optimization algorithms/protocols can be designed, implemented and experimented. In this section, we use routing as an example to demonstrate how higher-layer protocols can take advantage of PHY/MAC attributes (such as the channel status and the availability of multiple channels) for optimizing the performance.

Routing in ad hoc wireless networks has been an active area of research for many years. Much of the work in the area was motivated by the need to consider

energy constraints imposed by battery-powered nodes and to deal with node mobility. The research focus is thus to provide routes that are *resilient* to topology change in an *energy-efficient* manner. Unlike ad hoc wireless networks, most of the nodes in WMNs are stationary and thus dynamic topology changes are less of a concern. Also, wireless nodes in WMNs are mostly access points and Internet gateways and thus are not subject to energy constraints. As a result, the focus is shifted from maintaining network connectivity in an energy efficient manner to finding high-throughput routes between nodes, so as to provide users with the maximal end-to-end throughput. In particular, because multiple flows initiated by multiple nodes may engage in transmission at the same time, how to locate routes that give the minimal possible interference is a major issue.

The issue of locating interference-free (or interference-mitigated) routes has been addressed in the literature with roughly two complimentary approaches. First, some of the PHY/MAC attributes have been utilized to define better route metrics that yield high-throughput routes. Note that the conventional route metric is the hop count [69]–[71], and has been used in on-demand, ad-hoc routing protocols such as Ad-hoc On-demand Distance Vector (AODV) and Dynamic Source Routing (DSR). Use of this metric renders routes that are composed of long links. Due to the path loss effect over the distance, these long links are lossy and of low throughput [72]. The performance of routing protocols can be improved by better defining route metrics and explicitly taking into account the quality of wireless links. Second, each wireless node is usually equipped with one or more radios that can be switched among multiple non-overlapping channels. Use of multi-radios and multi-channels has thus been explored to construct interference-free/mitigated routes on which different channels are associated with different radios in order to eliminate intra- and inter-flow interference. The latter approach has been referred to as joint routing and channel assignment. In what follows, we first discuss several route metrics which have been proposed in the literature, and then summarize the various routing protocols with the taxonomy given in Fig. 4.5 as the roadmap.

4.4.1 Routing Metrics

Expected Transmission Count (ETX)

This metric calculates the expected number of transmissions (including retransmissions) needed to send a frame over a link, by measuring the forward and reverse delivery ratios between a pair of neighboring nodes [72]. To measure the delivery ratios, each node periodically broadcasts a dedicated *link probe* packet of a fixed size. The probe packet contains the number of probes received from each neighboring node during the last period. Based on these probes, a node can calculate the delivery ratio of probes on the link to and from each of its neighbors. The expected number of transmissions is then calculated as

$$ETX = \frac{1}{d_f \times d_r}$$

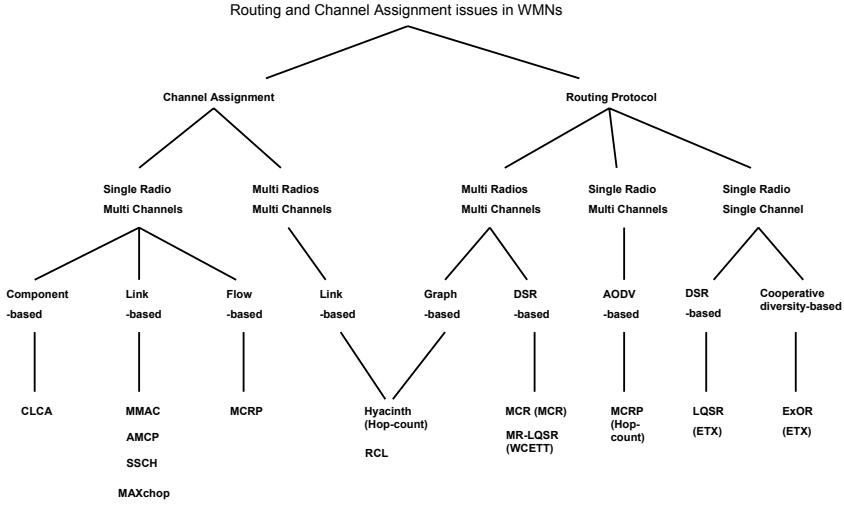


Fig. 4.5. A taxonomy of routing and channel assignment protocols for WMNs. Note that the routing metric that a routing protocol uses is given inside parentheses.

where d_f and d_r are the forward and reverse delivery ratio, respectively. With ETX as the route metric, the routing protocol can locate routes with the least expected number of transmissions. Note that the effects of link loss ratios and their asymmetry in the two directions of each link on a path are explicitly considered in the EXT measure. Measurements on wireless testbeds [16, 72] show that, for the source-destination pairs that are with two or more hops, use of ETX as the route metric renders routes with throughput significantly higher than use of the minimum hop count.

Expected Transmission Time (ETT)

One major drawback of ETX is that it may not be able to identify high-throughput routes, in the case of multi-radio, multi-rate wireless networks. This is because ETX only considers the packet loss rate on a link but not its bandwidth. ETT has thus been proposed to improve the performance of ETX in multi-radio wireless networks that support different data rates. Specifically, ETT includes the bandwidth of a link in its computation [73], i.e.,

$$ETT = ETX \times \frac{S}{B}$$

where S and B denote the size of the packet and the bandwidth of the link, respectively. ETT considers the actual time incurred in using the channel (excluding the

backoff time incurred in accessing the radio channel). In order to measure the bandwidth B of each link, a node sends two probe packets of different sizes (137 and 1137 bytes) to each of its neighbors every minute. The receiver node measures the difference between the instants of receiving the packets, and forwards the information to the sender. The bandwidth is then estimated by the sender node by dividing the larger packet size by the minimum of 10 consecutive measurements. Measurement results on a testbed show that use of ETT significantly improve the systems performance in a multiple-radio network.

Weighted Cumulative ETT (WCETT)

What ETX and ETT have not explicitly considered is the intra-flow interference. WCETT was proposed [73] to reduce the number of nodes on the path of a flow that transmit on the same channel. Specifically, let X_c be defined as the number of times channel c is used along a path. Then WCETT for a path is defined as the weighted sum of the cumulative expected transmission time and the maximal value of X_c among all channels, i.e.,

$$WCETT = (1 - \beta) \sum_{i=1}^n ETT_i + \beta \max_{1 \leq c \leq C} X_c \quad (4.1)$$

where β ($0 \leq \beta \leq 1$) is a tunable parameter. Reducing the first term of Eq. (4.1) improves the global resource utilization, while reducing the second term of Eq. (4.1) increases the achievable throughput by reducing the intra-flow interference. Moreover, the two terms also represent a trade-off between achieving low delay and high throughput. Reducing the first term reduces the delay, while reducing the second term increases the achievable link throughput. The tunable parameter β is used to adjust the relative importance of the two objectives.

Modified Expected Number of Transmissions (mETX) and Effective Number of Transmissions (ENT)

Another issue which ETX does not consider is the effect of short-term channel variation, i.e., ETX takes only the average channel behavior into account for the route decision. In order to capture the time-varying property of a wireless channel, the metrics mETX and ENT were proposed in [74] which took into account both the average and the standard deviation of the observed channel loss rates. Specifically, mETX is expressed as

$$mETX = \exp \left(\mu_{\Sigma} + \frac{1}{2} \sigma_{\Sigma}^2 \right)$$

where μ_{Σ} and σ_{Σ}^2 are the average and variability of the channel bit error probability. In some sense, mETX incorporates the impact of physical layer variability in the design of routing metrics. On the other hand, when the problem of maximizing aggregate throughput with the packet loss rate constraint is considered, mETX

may not be sufficient since the links which mETX selects may achieve the maximum link-layer throughput but incur high loss rates at the same time. The ENT metric is devised to meet both objectives. Specifically, ENT is expressed as

$$ENT = \exp(\mu_{\Sigma} + 2\delta\sigma_{\Sigma}^2)$$

where δ is the strictness of the loss rate requirement. As shown in both experimental and simulation results, mETX and ENT achieve a 50% reduction in the average packet loss rate as compared with ETX. This implies the effect of time-varying channels should be considered in designing a throughput-optimizing route metric.

4.4.2 Representative Routing Protocols

Link Quality Source Routing (LQSR)

LQSR [16] is a modified version of DSR and aims to select a better route using link-quality metrics in single-radio, single-channel wireless networks. LQSR implements the basic functionalities of DSR including route discovery and route maintenance. In addition, a variety of link quality metrics including ETX, Per-hop Round Trip Time (RTT) [75], Packet Pair [76] and hop count were supported as routing metrics.

LQSR is realized based upon the *Mesh Connectivity Layer (MCL)*, a loadable Microsoft Windows driver. It is located between layer 2 (link layer) and layer 3 (network layer) of the standard ISO/OSI model. To the higher layers, MCL appears to be another Ethernet link although it is a virtual one. To the lower layers, MCL appears to be another protocol running over the physical link. A basic functionality of this protocol is to monitor link quality continuously and change to the path that has the lowest overall cost. Metrics for monitoring the link quality for links actively in use are maintained by using a reactive mechanism.

Extremely Opportunistic Routing (ExOR)

ExOR [77] is a routing protocol that heavily leverages MAC attributes for data transfer. It aims to increase the throughput of large unicast transfers in single-radio, single-channel wireless networks. Central to ExOR is the notion of *cooperative diversity routing*. This notion was originally devised to avoid multi-path fading by using broadcasts to send information through multiple relays concurrently. This allows use of links which traditional routing would typically ignore.

ExOR broadcasts each packet and chooses a receiver to forward only after learning the set of nodes that actually receive the packet. ExOR attempts to send the packet as far as possible by selecting as the forwarding node the node that has the least distance to the final destination. In the course of packet forwarding, ExOR uses acknowledgments (ACKs) to ensure that only one node forwards the packet. This broadcast and forwarding approach takes advantage of “lucky” situations in which unanticipated receivers closer to the destination may be able help transport of the packet. In order to realize ExOR, a loss-rate matrix has to be available that contains the probability of successful packet reception between each pair of nodes. Such a

matrix can be built using, for example, a link-state flooding scheme. Every packet is required to include a set of forwarding candidates prioritized by the distance. The forwarding-decision is then based on the set of forwarding candidates found in the header of the received packet, and on the set of received ACKs which are sent following the receipt of the packet. The node which classifies itself as the forwarding node then retransmits the packet, using a new set of forwarding candidates. In addition, ExOR coordinates data sending between nodes with the use of a timed scheduling algorithm that gives preference to higher priority nodes and ensures collisions do not occur.

Experimental results performed on MIT Roofnet show that ExOR improves the throughput by a factor of 2 or 4 over ETX since it uses multiple relay nodes to forward the packet to its destination. It is also shown that the total number of transmissions required to route a packet from a source to its corresponding destination can be improved by 55-65% in comparison to the best predetermined route from the wired model.

Multi-Channel Routing Protocol (MCRP)

MCRP [78] is a routing protocol that is specifically designed for multi-channel networks with single-radio nodes and exploits a channel switching technique. MCRP assigns channels to data flows rather than assigning channels to nodes. Thus, all nodes on the path on which a data flow traverses are assigned to a common channel. This approach is well-suited for on-demand routing where channels are assigned in conjunction with the route discovery procedure. The advantage of this approach is that once the route is established, nodes do not need to switch channels for the duration of the flow. Moreover, because this approach attempts to allocate different channels to different flows, it allows simultaneous transmissions and improves network capacity.

In the route discovery phase, a node with packets to send broadcasts a Route Request (RREQ) packet on each channel in a round robin manner. A RREQ packet contains the channel table and the flow table to be propagated to the destination. The channel table contains the number of times a channel has been consecutively used on a single flow path, and the flow table contains the number of times simultaneous flows have been carried out on a single channel. These tables are used by the destination node to select a feasible and load balancing route. Upon receipt of a RREQ packet, a node also rebroadcasts the RREQ (unless it itself is the destination). Moreover, the node also creates a reverse path to the source and maintains the information of the channel on which the RREQ arrives. Upon receipt of one or more RREQ packets, the destination prepares a Route Reply (RREP) packet (that contains the selected channel) and unicasts it on the selected path. All nodes that have forwarded the corresponding RREQ packet change their operating channels to the channel selected by the destination.

Multi-Radio Link Quality Source Routing (MR-LQSR)

MR-LQSR is essentially the LQSR protocol with the use of the WCETT metric [73]. Similar to LQSR, MR-LQSR also operates in conjunction with the Mesh Connectivity Layer (MCL). It has three main objectives: (i) the loss rate and the bandwidth of

a link should be taken into account for selecting a path; (ii) the path metric should be increasing; and (iii) the path metric should reflect the throughput degradation due to the interference caused by simultaneous transmissions. Towards these objectives, WCETT is considered as a path metric to account for the interference among links on the same channel.

To incorporate WCETT into LQSR, the information including the channel assigned on a link, its bandwidth and loss rate is propagated to all nodes in the network, in the form of DSR control packets. To calculate WCETT, the ETT on each link is first computed using the ETX, the bandwidth and the packet loss. The ETT metric is then used to compute the WCETT. Finally, the WCETT is applied to the link cache scheme of the DSR protocol. In native DSR, since the default cost of each link is set to one, the Dijkstra algorithm, when executed over the link cache by a source node, always gives the shortest path with the minimum hops. On the other hand, when the WCETT is used as the link cost, it produces the minimal cost path in terms of link bandwidth and loss rate.

Multi-Channel Routing (MCR)

MCR [79] is an on-demand, multi-channel routing protocol for WMNs with multi-radio nodes. In order to fully exploit the available channels with a limited number of radios on each node, the protocol uses a switching mechanism to change channels assigned to a radio interface whenever necessary. In particular, two types of interfaces are assumed: fixed and switchable. K interfaces out of a total M interfaces are fixed interfaces and are designated to some K channels. The remaining interfaces are dynamic interfaces and dynamically assigned to any of the remaining channels. Multiple queues are maintained for all switchable interfaces.

Each node maintains a neighbor table and a channel usage list. The neighbor table contains the fixed channels used by the node's neighbors. The channel usage list contains the count of two-hop neighborhoods that are using a channel as their fixed channel. Each node periodically transmits a HELLO packet on all channels, including its fixed channel number and neighbor table. A node receiving the HELLO packet then updates its neighbor table and channel usage list. The table and list information are used for the switching mechanism to make a decision of which channel is assigned to what interface in the link layer. Furthermore, the switching mechanism helps MCR for selecting routes over multiple channels.

The route used in MCR is a weighted sum of two elements. The first element accounts for the resources consumed along the path and is obtained by summing ETT values along the path. Note that because the switching cost is (implicitly) part of the ETT of each link, the first term contains the switching cost. The second term accounts for the channel diversity cost, and is calculated by finding the maximum ETT cost on all channels. Accordingly, a route with a larger number of distinct channels may have a lower diversity cost. Different from WCETT which is designed for the case in which the number of interfaces per node is equal to the number of channels, the MCR metric is applicable to a more general case where the number of available interfaces may be smaller than the number of available channels, and interface switching is needed.

The route discovery phase of MCR is similar to that of DSR. In addition, each RREQ also contains the channel number and the switching cost. Thus, when the RREQ is received by destination, the diversity cost (i.e., the number of channels in the RREQ) and the switching cost (i.e., the sum of all link switching costs) are calculated. Based on these costs, the destination selects the optimal path available between the source and the destination.

Joint Routing and Channel Allocation

Alicherry *et al.* [80] proposed a joint routing, channel assignment and link scheduling (RCL) algorithm that attempts to maximize throughput in a multi-channel and multi-radio network. The work is performed under the premise that topology change in WMNs is infrequent and the variability of aggregate traffic demand from each mesh router (client traffic aggregation point) is small. These characteristics allow optimization to be made periodically by the system management software based on traffic demand estimates. Under the assumption that the network is restricted to be a superset of a disk graph (i.e., the interference range is assumed to be a fixed multiple of the communication range), the authors mathematically formulated the joint channel assignment and routing problem taking into account interference constraints, the number of channels in the network, and the number of radios available at each mesh router. They then solved the problem with the use of the LP relaxation technique. This was then followed by (i) several adjustment steps to obtain a valid channel assignment and a link scheduling policy that eliminates interference; and (ii) a post processing phase and a flow scaling round to make the assignment interference-free.

Hyacinth Network Architecture that Supports Channel Assignment and Routing

Raniwala and Chiueh [81] proposed a network architecture, called *Hyacinth*, for wireless mesh networks with multi-channels and multi-radios. This architecture supports a fully distributed channel assignment algorithm and a spanning-tree based routing algorithm. The mesh routers having access to the wired network are considered as the root nodes of the spanning tree. Based on the spanning tree, routing is performed to balance traffic load over the network as well as to repair route failures. The channel assignment algorithm operates in two phases: *neighbor interface binding* and *interface-channel assignment*. In the first phase each node classifies its interfaces into the set of network interface cards (NICs) for its parent node termed as UP-NICs and the set of NICs for its children nodes termed as DOWN-NICs. Each node can assign and change the channel on its DOWN-NICs only. The purpose of this phase is to bound the impact of change in channel assignment since the change may cause a series of channel re-assignment across the network. In the second phase each node periodically exchanges messages that contain the channel usage status with its neighbors in the interference range. Based on the status of channels used in the neighborhood, a node then determines a set of channels that are least-used in its vicinity. The advantage of this channel assignment scheme is that it achieves a tree architecture where links close to the root of the spanning tree are given higher bandwidth.

The channel assignment is further combined with the routing process. Each node which has routing information to the root advertises this information to one-hop neighbors containing the cost metrics such as the hop-count and the residual uplink capacity. Based on the cost, each node which receives the advertisement makes a decision with regard to joining the advertising node. If the node decides to join, it sends an acceptance message to the advertising node and a departing message to its parent node with which it is now associated. The joining process for new nodes to the network is initiated by broadcasting HELLO packets to the neighboring nodes.

4.5 Open Research Issues

In spite of the bulk of research in the literature, there are still open research issues that should be addressed in order to build high-performance and robust WMNs. In this section, we outline these open research issues.

Topology Control Under the Physical SINR Model

As mentioned in Section 4.2.1, most of the studies on topology control are inherently based on the graph model that characterizes graph-theoretic properties of wireless networks, while ignoring important physical aspects of communications. Recently, Moscibroda et al. [30] studied the problem of topology control under an information-theoretic SINR model. They derived the time complexity of a scheduling algorithm that assigns transmit power levels to all the nodes and schedules all links of an arbitrary network topology. They proved that if the signals are transmitted with correctly assigned transmission power levels, the number of time slots required to successfully schedule all links is proportional to the squared logarithm of the network size. They also devised a centralized algorithm for approaching the theoretical upper bound. In spite of its theoretical importance, the centralized scheduling algorithm cannot, however, be practically implemented. Devising *localized* topology control algorithms under the physical SINR model remains as a research challenge.

Channel Assignment and Routing in Multi-radio, Multi-channel Environments

A traditional channel assignment problem is what channel should be assigned to a transmission pair in order to enable transmission, mitigate inter-/intra-interference, and improve network capacity. This problem is augmented with another dimension in multi-radio and multi-channel environments: what channel should be associated with each of the radio interfaces a node possesses? Although there have been some preliminary work [79, 82], a rigorous treatment of this problem has been lacking. This problem is further complicated, when it is considered in conjunction with routing. Several research efforts [79–81] have been made to address the joint problem of channel assignment and routing, and various heuristics (although with insightful theoretical base) have been proposed under certain (perhaps unrealistic) interference models. The challenge, however, remains to consider the problem in an analytic framework under a realistic interference model (in which cumulative interference due to concurrent transmissions is faithfully characterized).

Tuning All the PHY/MAC Control Knobs for Spatial Reuse

As mentioned in Section 4.2, there are several PHY/MAC attributes that can be used to improve spatial reuse, mitigate interference and maximize network capacity: (i) the *transmit power* each node uses for communications, (ii) the *carrier sense threshold* each node uses to determine if the shared medium is idle, (iii) the *channel* on which the node transmits, and (iv) the *time intervals* in which each node gain access to the channel. On top of all these, routing also plays an important role in mitigating interference and improving end-to-end throughput. Most existing work has only focused on tuning one or two attributes, in spite of the fact that these attributes actually intertwined with each other. The challenge remains to establish an optimization framework of maximizing the network capacity by adjusting PHY/MAC parameters in all possible dimensions in the design space.

Routing Metrics that Leverage PHY/MAC Attributes

As discussed in Section 4.4.1, several routing metrics have been proposed based on the link transmission time (estimated by probe packets). There are, however, a much richer set of PHY/MAC attributes that can be leveraged for cross-layer design and implementation (Section 4.3). Incorporating some of these PHY/MAC attributes in the calculation of routing metrics may render better, higher-throughput routes and further improve the overall network performance.

Overheads Incurred in Cross-Layer Design and Optimization

Most of the theoretical results that demonstrate the advantage of cross-layer design and optimization in WMNs do not adequately consider the computing and communications overhead thus incurred, i.e., the overhead incurred in collecting information needed for inferring the interference, calculating the route metrics, switching the channels, or scheduling frame transmission. It is thus not clear whether or not the performance gain in engaging multiple protocol entities in the protocol stack or across the network outweighs the overhead thus incurred. An in-depth empirical study on a large WMN is needed to better quantify the overhead.

Considering Mesh Client Characteristics in WMNs

In WMNs, there are roughly two entities: mesh routers and mesh clients. The former is usually stationary and not energy-constrained, while the latter is battery-powered and may move arbitrarily. Most of the existing studies have focused on MAC and routing on mesh routers, without considering the characteristics of mesh clients. Incorporating the end-to-end performance requirements and constraints of mesh clients into WMN design will be an interesting and challenging research issue.

Conclusion

By virtue of their robustness, cost-effectiveness, self-organizing and self-configuring nature, WMNs have emerged as a new network paradigm for a wide range of applications, such as public safety and emergency response communications, intelligent transportation systems, and community networks. One fundamental problem of WMNs with a limited number of radio interfaces and orthogonal channels is that the performance degrades significantly as the network size grows. This results from increased interference between nodes and diminished spatial reuse over the network.

In this chapter, we have addressed several research issues pertinent to the performance and capacity optimization issues in WMNs. We have provided a taxonomy of recent advances in the literature with respect to radio resource management (adjusting transmission rate, power, carrier sense threshold and assigning channels) and routing. We have also addressed important issues regarding design and implementation of device driver support that facilitates cross layer design and optimization. Finally, we have outlined several research avenues in which future research can pursue.

References

1. Microsoft Networking Research Group, "Self-organizing neighborhood wireless mesh networks," <http://research.microsoft.com/mesh/>.
2. Nortel Networks, "The business case for wireless mesh networks," http://www.nortelnetworks.com/corporate/events/2003d/wmn_eseminar/colateral/wmn_eseminar.pdf, December 2003.
3. Bay Area Wireless Users Group, <http://www.bawug.org/>.
4. CUWiN, <http://www.cuwireless.net/>.
5. SFLan, <http://www.sflan.org>.
6. Seattle Wireless, <http://www.seattlewireless.net/>.
7. Southampton Open Wireless Network, <http://www.sown.org.uk/>.
8. Wireless Leiden, <http://www.wirelessleiden.nl/>.
9. MIT Roofnet, <http://pdos.csail.mit.edu/roofnet/doku.php>.
10. Technology for All Wireless, <http://tfa.rice.edu/>.
11. D. Aguayo, J. Bicket, S. Biswas, G. Judd, and R. Morris, "Link-level measurements from an 802.11b mesh network," in *Proc. of ACM SIGCOMM*, September 2004.
12. J. Bicket, D. Aguayo, S. Biswas, and R. Morris, "Architecture and evaluation of an 802.11b mesh network," in *Proc. of ACM MobiCom*, September 2005.
13. Z. Fu, H. Luo, P. Zerfos, S. Lu, L. Zhang, and M. Gerla, "The impact of multihop wireless channel on TCP performance," *IEEE Trans. on Mobile Computing*, vol. 4, no. 2, pp. 209–221, March/April 2005.
14. D. Berger, Z. Ye, P. Sinha, S. Krishnamurthy, M. Faloutsos, and S. K. Tripathi, "TCP-friendly medium access control for ad-hoc wireless networks: Alleviating self-contention," in *Proc. of IEEE MASS*, October 2004.
15. K. Sanzgiri, I. D. Chakeres, and E. M. Belding-Royer, "Determining intra-flow contention along multihop paths in wireless networks," in *Proc. of Broadnets Wireless Networking Symposium*, October 2004.

16. R. Draves, J. Padhye, and B. Zill, "Comparison of routing metrics for static multi-hop wireless networks," in *Proc. of ACM SIGCOMM*, 2004.
17. A. Akella, G. Judd, P. Steenkiste, and S. Seshan, "Self management in chaotic wireless deployments," in *Proc. of ACM MobiCom*, 2005.
18. A. Miu, H. Balakrishnan, and C. E. Koksal, "Achieving loss resiliency through multi-radio diversity in wireless networks," in *Proc. of ACM MobiCom*, 2005.
19. L. Li, J. Halpern, V. Bahl, Y. Wang, and R. Wattenhofer, "Analysis of a cone-based distributed topology control algorithm for wireless multi-hop networks," in *Proc. of ACM Symposium on Principle of Distributed Computing (PODC)*, 2001, pp. 264–273.
20. N. Li and J. C. Hou, "FLSS: A fault-tolerant topology control algorithm for wireless networks," in *Proc. of ACM MobiCom*, 2004.
21. —, "Topology control in heterogeneous wireless networks: Problems and solutions," in *Proc. of IEEE INFOCOM*, March 2004.
22. —, "Localized topology control algorithms for heterogeneous wireless networks," *IEEE/ACM Trans. on Networking*, vol. 13, no. 6, pp. 1313–1324, December 2005.
23. —, "Localized fault-tolerant topology control in wireless ad hoc networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 17, no. 4, pp. 307–320, April 2006.
24. N. Li, J. C. Hou, and L. Sha, "Design and analysis of a MST-based distributed topology control algorithm for wireless ad-hoc networks," *IEEE Trans. on Wireless Communications*, vol. 4, no. 3, pp. 1195–1207, 2005.
25. R. Ramanathan and R. Rosales-Hain, "Topology control of multihop wireless networks using transmit power adjustment," in *Proc. of IEEE INFOCOM*, March 26–30, 2000.
26. V. Rodoplu and T. Meng, "Minimum energy mobile wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 8, pp. 1333–1344, August 1999.
27. R. Wattenhofer, L. Li, P. Bahl, and Y.-M. Wang, "Distributed topology control for power efficient operation in multihop wireless ad hoc networks," in *Proc. of IEEE INFOCOM*, April 22–26, 2001.
28. R. Prim, "Shortest connection networks and some generalizations," *The Bell System Technical Journal*, vol. 36, pp. 1389–1401, 1957.
29. M. Burkhart, P. Rickenbach, R. Wattenhofer, and A. Zollinger, "Does topology control reduce interference?" in *Proc. of ACM MobiHoc*, May 2004.
30. T. Moscibroda, R. Wattenhofer, and A. Zollinger, "Topology control meets SINR: The scheduling complexity of arbitrary topologies," in *Proc. of ACM MobiHoc*, June 2006.
31. Y. Gao, J. C. Hou, and H. Nguyen, "Physical-model-based topology control for maintaining network connectivity and maximizing network capacity," in *Proc. of IEEE Int'l Conf. on Network Protocols*, October 2007.
32. H. Lim, C. Lim, and J. C. Hou, "A coordinate-based approach for exploiting temporal-spatial diversity in wireless mesh networks," in *Proc. of ACM MobiCom*, September 24–29, 2006.
33. J. Monks, V. Bharghavan, and W.-M. Hwu, "A power controlled multiple access protocol for wireless packet networks," in *Proc. of IEEE INFOCOM*, April 22–26, 2001.
34. A. Muqattash and M. Krunz, "Power controlled dual channel (PCDC) medium access protocol for wireless ad hoc networks," in *Proc. of IEEE INFOCOM*, March 30–April 3, 2003.
35. —, "A single-channel solution for transmission power control in wireless ad hoc networks," in *Proc. of ACM MobiHoc*, May 24–26, 2004.
36. S. Narayanaswamy, V. Kawadia, R. Sreenivas, and P. R. Kumar, "Power control in ad-hoc networks: Theory, architecture, algorithm and implementation of the COMPOW protocol," in *European Wireless Conference*, 2002.

37. T. Nadeem, L. Ji, A. Agrawala, and J. Agre, "Location enhancement to IEEE 802.11 DCF," in *Proc. of IEEE INFOCOM*, March 13–17, 2005.
38. A. Vasan, R. Ramjee, and T. Woo, "ECHOS: Enhanced capacity 802.11 hotspots," in *Proc. of IEEE INFOCOM*, March 13–17 2005.
39. J. Zhu, X. Guo, L. Yang, and W. S. Conner, "Leveraging spatial reuse in 802.11 mesh networks with enhanced physical carrier sensing," in *Proc. of IEEE ICC*, June 20–24, 2004.
40. J. Zhu, X. Guo, L. Yang, W. S. Conner, S. Roy, and M. M. Hazra, "Adapting physical carrier sensing to maximize spatial reuse in 802.11 mesh networks," *Wiley Wireless Communications and Mobile Computing*, vol. 4, pp. 933–946, December 2004.
41. X. Yang and N. H. Vaidya, "On the physical carrier sense in wireless ad hoc networks," in *Proc. of IEEE INFOCOM*, March 13–17, 2005.
42. Z. Zeng, Y. Yang, and J. C. Hou, "How physical carrier sense affect protocol capacity: modeling and analysis," Dept. of Computer Science, University of Illinois at Urbana Champaign, Tech. Rep., April 2007.
43. F. Cali, M. Conti, and E. Gregori, "IEEE 802.11: Design and performance evaluation of an adaptive backoff mechanism," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 9, September 2000.
44. H. Zhai and Y. Fang, "Physical carrier sensing and spatial reuse in multirate and multihop wireless ad hoc networks," in *Proc. of IEEE INFOCOM*, April 23–29, 2006.
45. J. A. Fuemmeler, N. H. Vaidya, and V. V. Veeravalli, "Selecting transmit powers and carrier sense thresholds for CSMA protocols," Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Tech. Rep., October 2004.
46. T.-S. Kim, H. Lim, and J. C. Hou, "Improving spatial reuse through tuning transmit power, carrier sense threshold, and data rate in multihop wireless networks," in *Proc. of ACM MobiCom*, September 24–29, 2006.
47. Y. Yang, J. C. Hou, and L.-C. Kung, "Modeling of physical carrier sense in multi-hop wireless networks and its use in joint power control and carrier sense adjustment," in *Proc. of IEEE INFOCOM Miniconferences*, May 6–12, 2007.
48. G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, March 2000.
49. A. Kumar, E. Altman, D. Miorandi, and M. Goyal, "New insights from a fixed point analysis of single cell IEEE 802.11 WLANs," in *Proc. of IEEE INFOCOM*, April 2005.
50. IEEE Computer Society, "Part 11: Wireless LAN Medium Access (MAC) and Physical Layer (PHY) Specifications, Amendment 8: Medium Access Control (MAC) Quality of Service Enhancement," *IEEE Standard 802.11e*, 2005.
51. J. So and N. H. Vaidya, "Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver," in *Proc. of ACM MobiHoc*, 2004.
52. J. Shi, T. Salonidis, and E. Knightly, "Starvation mitigation through multi-channel coordination in CSMA multi-hop wireless networks," in *Proc. of ACM MobiHoc*, May 2006.
53. A. Mishra, V. Shrivastava, D. Agarwal, S. Banerjee, and S. Ganguly, "Distributed channel management in uncoordinated wireless environments," in *Proc. of ACM MobiCom*, September 2006.
54. R. Vedantham, S. Kakumanu, S. Lakshmanan, and R. Sivakumar, "Component based channel assignment in single radio, multichannel ad hoc networks," in *Proc. of ACM MobiCom*, September 2006.
55. P. Bahl, R. Chandra, and J. Dunagan, "SSCH: Slotted seeded channel hopping for capacity improvement in IEEE 802.11 ad-hoc wireless networks," in *Proc. of ACM MobiCom*, 2004.

56. J. Bicket, "Bit-rate selection in wireless networks," Master's thesis, MIT, 2005.
57. I. Haratcherev, K. Langendoen, R. Lagendijk, and H. Sips, "Hybrid rate control for IEEE 802.11," in *Proc. of ACM MobiWac*, 2004.
58. —, "Fast 802.11 link adaptation for real-time video streaming by cross-layer signaling," in *Proc. of ISCAS*, 2005.
59. G. Holland, N. H. Vaidya, and P. Bahl, "A rate-adaptive MAC protocol for multi-hop wireless networks," in *Proc. of ACM MobiCom*, 2001.
60. A. Kamerman and L. Monteban, "WaveLAN II: A high-performance wireless LAN for the unlicensed band," *Bell Labs Technical Journal*, 1997.
61. J. Kim, S. Kim, S. Choi, and D. Qiao, "CARA: Collision-aware rate adaptation for IEEE 802.11 WLANs," in *Proc. of IEEE INFOCOM*, 2006.
62. M. Lacage, M. H. Manshaei, and T. Turletti, "IEEE 802.11 rate adaptation: A practical approach," in *Proc. of ACM MSWiM*, 2004.
63. D. Qiao and S. Choi, "Fast-responsive link adaptation for IEEE 802.11 WLANs," in *Proc. of IEEE ICC*, 2005.
64. D. Qiao and K. Shin, "Achieving efficient channel utilization and weighted fairness for data communications in IEEE 802.11 WLAN under the DCF," in *Proc. of International Workshop on Quality of Service 2002*, May 2002.
65. B. Sadeghi, V. Kanodia, A. Sabharwal, and E. Knightly, "Opportunistic media access for multirate ad hoc networks," in *Proc. of ACM MobiCom*, 2002.
66. S. H. Y. Wong, H. Yang, S. Lu, and V. Bharghavan, "Robust rate adaptation for 802.11 wireless networks," in *Proc. of ACM MobiCom*, September 24–29, 2006.
67. L.-C. Kung, J. Choi, J. C. Hou, Y. Gao, I.-H. Hou, R. Lam, and Y. Yang, "Toward building an open wireless mesh network for cross layer design and optimization," Dept. of Computer Science, University of Illinois at Urbana-Champaign, Tech. Rep., May 2007.
68. MADWIFI, <http://sourceforge.net/projects/madwifi>.
69. V. D. Park and M. S. Corson, "A highly adaptive distributed routing algorithm for mobile wireless networks," in *Proc. of IEEE INFOCOM*, 1997.
70. C. E. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers," in *Proc. of ACM SIGCOMM*, 1994.
71. C. E. Perkins and E. M. Royer, "Ad-hoc on demand distance vector routing," in *Proc. of IEEE Workshop on Mobile Computing Systems and Applications*, 1999.
72. D. S. J. De Couto, D. Aguayo, J. C. Bicket, and R. Morris, "A high-throughput path metric for multi-hop wireless routing," in *Proc. of ACM MobiCom*, 2003.
73. R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. of ACM MobiCom*, 2004.
74. C. Koksai and H. Balakrishnan, "Quality-aware routing metrics for time-varying wireless mesh networks," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 11, pp. 1984–1994, Nov. 2006.
75. A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, "A multi-radio unification protocol for IEEE 802.11 wireless networks," in *Proc. of IEEE BroadNets*, July 2004.
76. S. Keshav, "A control-theoretic approach to flow control," *Proc. of the conference on Communications architecture and protocols*, pp. 3–15, 1993.
77. S. Biswas and R. Morris, "ExOR: Opportunistic routing in multi-hop wireless networks," in *Proc. of ACM SIGCOMM*, September 2005.
78. J. So and N. H. Vaidya, "Routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver," Dept. of Computer Science and Coordinated Science Laboratory, University of Illinois at Urbana-Champaign, Tech. Rep., 2004.

79. P. Kyasanur and N. H. Vaidya, "Routing and link-layer protocols for multi-channel multi-interface ad hoc wireless networks," University of Illinois at Urbana-Champaign, Tech. Rep., May 2005.
80. M. Alicherry, R. Bhatia, and L. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," in *Proc. of ACM MobiCom 2005*, September 2005.
81. A. Raniwala and P. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *Proc. of IEEE INFOCOM*, 2005.
82. M. Benveniste, "The CCC mesh MAC protocol," IEEE 802.11-05/0610r1, 2005.